Abstract

Webber, David Wayne. Control of HVAC Dampers by Trans-Permanent Magnetics. (Under the direction of Dr. Larry Silverberg)

In recent years, the nation has come under an energy crunch. The energy crisis is in part due to inefficient energy use in actuators. Recent advancements in trans-permanent magnetics, will allow this new technology to be employed in actuators that will require significantly less energy. Applications such as spacecraft pointing and deployment, along with air valve actuation have already proven feasible. The applications for trans-permanent magnetics vary from solenoids to motors, with evident benefits of low power, and no wear.

The purpose of this thesis is to develop and implement a trans-permanent magnetic actuator for HVAC dampers. The system will use a minimal number of magnets and will utilize magnetic forces for soft latching of the device in its open and closed states. The scope of this project includes mounting an HVAC damper in a moderate air stream, the design of a trans-permanent actuator, and evaluation of the actuator. The air flow through the duct is higher than typically found in residential or commercial HVAC systems. The actuator will rely upon onboard magnetization to operate the damper's louvers. The onboard magnetization process will occur through an impulse magnetizing circuit. Several experimental tests were conducted on the prototype actuator to test performance and limitations. The results of these experiments demonstrate a working unoptimized trans-permanent magnetic actuator.

Control of HVAC Dampers by Trans-Permanent Magnetics

by

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Biography

I, David Webber, grew up in Goldsboro, NC, a small town about 45 miles east of Raleigh, NC. My brothers, James and Joseph and I were raised by our parents Patricia and Jimmy Webber. I graduated from Eastern Wayne High School in 1997. Upon graduation I decided to take some time off from my academic career. After two years of working in craftsmen type jobs in the Goldsboro area, I began college at North Carolina State University in 1999. Growing up in Goldsboro, I spent most of my time working with my grandfather Harold Webber learning how to fabricate and fix anything from industrial equipment to household appliances. The experience and knowledge my grandfather instilled in me, along with my parents encouragement, prompted my study in mechanical engineering. I graduated in May 2003 with a Bachelor of Science in Mechanical Engineering. I began graduate school in the fall of 2003 and will graduate in the fall of 2005.

Acknowledgements

I would like to thank my parents and grandparents for giving me the opportunity to pursue a college career and supporting me throughout my endeavors.

Thanks to my graduate committee, Dr. Ngaile and Dr. Ramasubramanian for allowing me to do such an interesting research project.

Thanks also to my graduate advisor, Dr. Silverberg, who gave me guidance and focus throughout this project.

I would like to thank my friend Dr. Louis Duval, who I met as an undergraduate when he was a teaching assistant, for introducing me to the technology of trans-permanent magnetics. I would also like to thank him for introducing me to Dr. Silverberg, and encouraging him to take me on as a graduate student.

I would also like to thank all my friends that I have met while working in the undergraduate senior design lab during my graduate career, for their encouragement and advice, Dale Myatt, Robert Hughes, Sigmon Sheldon, Dr. Chau Tran, Sarah Fisher, and Jennifer McCraw.

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Nomenclature

C	=	Capacitance
d	=	Diameter
d_m	=	Magnet diameter
d_w	=	Wire diameter
H	=	Magnetic field strength
i	=	Current
l	=	Magnet length
L	=	Electromagnetic coil inductance
n	=	Number of turns per layer
N	=	Number of turns
N_L	=	Number of layers
r	=	Gear radius
R_C	=	Charging resistor
R_D	=	Electromagnetic coil resistance
R_{TOTAL}	=	Total electromagnetic coil resistance
R_W	=	Resistance per unit length
T	=	Applied moment
U_{E1-2}	=	Electrical work done
U_{M1-2}	=	Mechanical work done
V	=	Direct current power source
θ	=	Angle of the louvers

1. Introduction

The need for greater energy efficiency in actuators is recognized public policy [See, for example, [1]). Also, in the engineering community, it is recognized that energy efficiency can reduce wear and increase actuator lifetime. Thus, an incentive exists for the development of energy efficient actuators.

1.1 Purpose

A significant level of inefficiency occurs when an actuator is idle. The level of inefficiency is particularly high in actuators that are used intermittently. In particular, dampers used in heating, ventilation, and air conditioning (HVAC) are controlled intermittently. In this thesis, an approach is presented aimed at developing energy efficient actuators for control of dampers in the HVAC industry.

For the purposes of this discussion, assume that an actuator has two states – open and closed. The actuator expends energy to move from one state to another. Energy is also expended to hold the system in one or both of its states, i.e., to maintain it in an idle state. The question arises how to eliminate this portion of the energy expended.

The energy in a system can be eliminated while it is idle provided another means is introduced to hold the system in a state. For example, a latch can be designed to hold a

system in a state [2]. When a latch is used, care must be exercised in the design process to ensure that the associated latching energy is small and that it does not significantly increase design complexity. This thesis presents a different approach to holding a system in a state and to moving it from one state to another. The approach is based on recent developments in trans-permanent magnetics.

This thesis studies the feasibility of the HVAC damper application. Toward this end, a trans-permanent actuator is designed for a representative HVAC damper (See Fig. 1). The intent is to evaluate the design process, the constraints that arise, and other unforeseen factors.

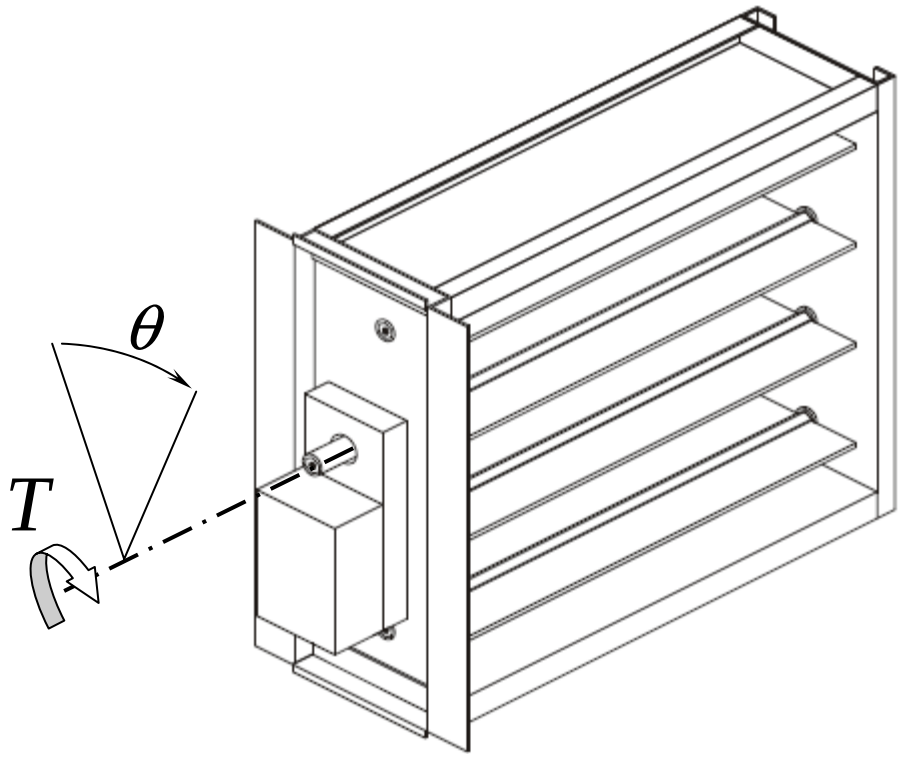


Figure 1: HVAC damper [3]

1.2 Brief History of Trans-permanent Magnetics

Trans-permanent magnetics is defined as the on-board process by which the polarity of a permanent magnet is switched [4]. Trans-permanent magnetics was recently applied to spacecraft systems for pointing, shape control, and deployment [5], to valves [6], and to motors [7]. This thesis applies, for the first time, trans-permanent magnetics to HVAC dampers.

The basic idea in trans-permanent magnetics is to use the magnetic force of a permanent magnet to hold a system in a given state and to use the permanent magnets and an electromagnet together to move the system from one state to another. The electromagnet also polarizes the permanent magnet while the state is changing.

2. Literature Review

Trans-permanent magnetics is a reasonably new technology; only three journal article have been published in the past. These three journal article discuss the analysis of trans-permanent magnetic systems, trans-permanent magnetic actuation for spacecraft, and low power valve actuation with trans-permanent magnetics.

Silverberg and Duval [4] outline the analysis of trans-permanent magnetic systems. The article develops the method of switching the states of permanent magnets, which is now referred to as trans-permanent magnetics. The paper contains the governing equations needed for analysis, and demonstrates the feasibility of the concept through experimentation. Below in Fig. 4 the experimental setup for this paper is shown.

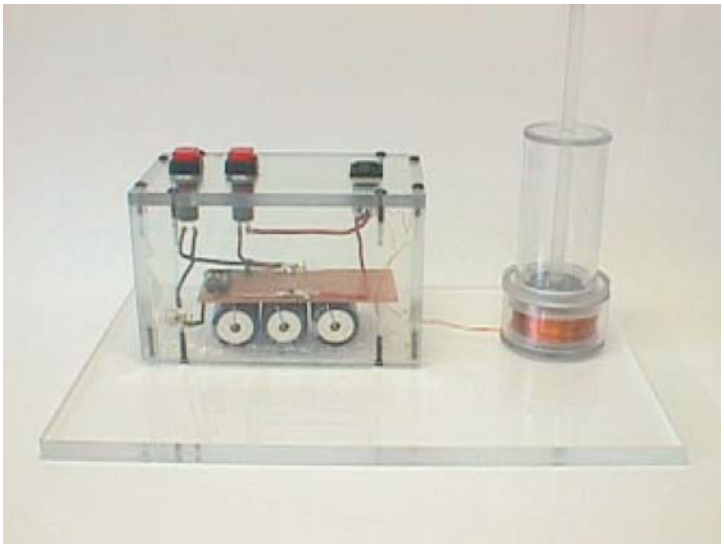


Figure 2: T-PM experimental setup [4]

Silverberg and Farmer [5] show that trans-permanent magnetics are well suited for spacecraft point, shape control, and deployment. The system is shown to be able to hold devices in

position with specified constraints, and periodically change position. The devices are shown to experience little wear and fatigue while expending no power during regulation. The actuators would do very well in spacecraft due to the fact they require little power and hold there position for long periods of time with out power.

Silverberg and Duval [6] uses trans-permanent magnetics in the design of an ultra-low-power valve. The trans-permanent magnetics were configured in a linear stack and the relationship between strength and number of magnets in the stack was studied. The stacked configuration would allow for variation in the stroke of the valve. Figure 3 shows the prototype valve containing 5 permanent magnets.

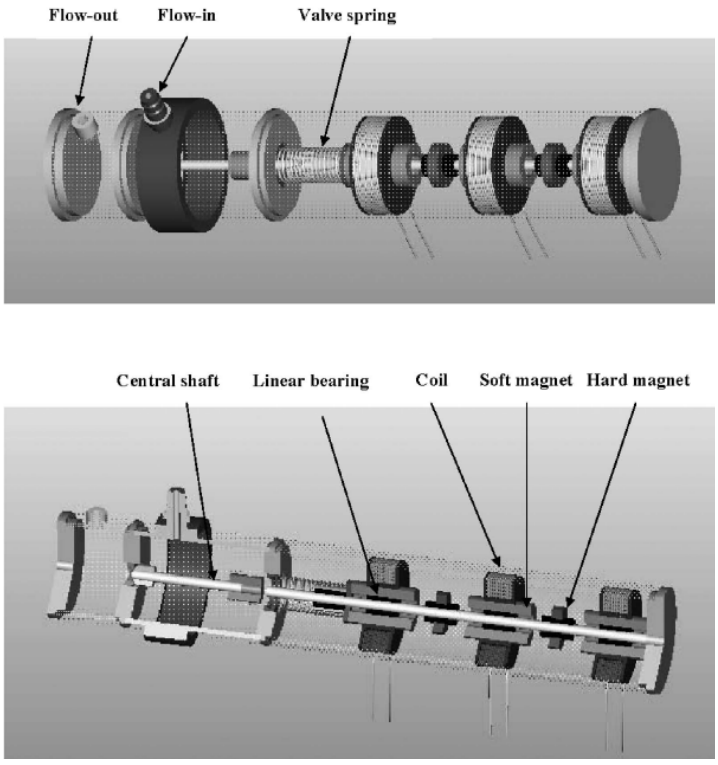


Figure 3: T-PM valve using linear stacks [6]

3. Problem Statement

Figure 4 shows a typical trans-permanent magnetic system. The system consists of a non-tunable (hard) permanent magnet, a tunable (soft) permanent magnet surrounded by a polarizing coil, an *RC* charging circuit and an *LRC* discharging circuit. For example, assume that the permanent magnets are initially attracted to each other. The force of attraction would hold the magnets in its initial state. Then, assume that the circuit discharges current into the coil, producing a rapid electromagnetic pulse. The pulse re-polarizes the tunable permanent magnet, producing a steady-state repulsive force between the permanent magnets. The pulse also produces a transient repulsive electromagnetic force between the magnets. The repulsive forces of the permanent magnet and the electromagnet move the system to a new state.

The following design features are apparent. With respect to latching, notice that the permanent magnets perform the latching, so the latching is soft. Soft latching eliminates the failure mode associated with mishandling. Next, notice that the soft magnet's strength, because it's being re-polarized, does not decrease over time. The weakening of soft permanent magnets over time, which is another failure mode in electromagnetic devices, is eliminated. Finally, notice that the steady-state permanent magnetic force and the transient electromagnet force are both repulsive when the pulse is being applied and are hence complimentary. In typical latching mechanisms the opposite occurs: The latch force needs to be overcome by the force that moves the system from one state to another.

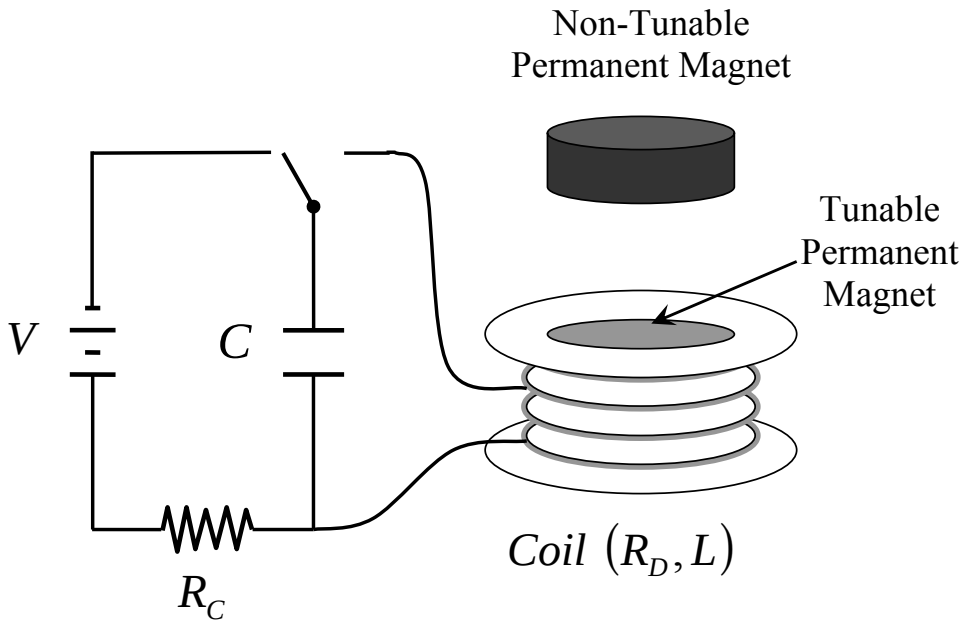


Figure 4: Trans-permanent magnetic system

The basic question addressed in this paper is whether trans-permanent magnetics can be applied to HVAC dampers. To answer this question, a control system for a representative HVAC damper was designed and tested.

In terms of work done, the purpose of the control system is to convert the work done by permanent magnets and an electromagnet into a mechanical form that opens and closes the louvers in an HVAC damper placed in a duct while a flow of air is passing through the duct. The mechanical work done is $U_{M1-2} = \int_{(1)}^{(2)} T d\theta$ in which T is an applied moment and θ is the angle of the louvers (See Fig. 5).

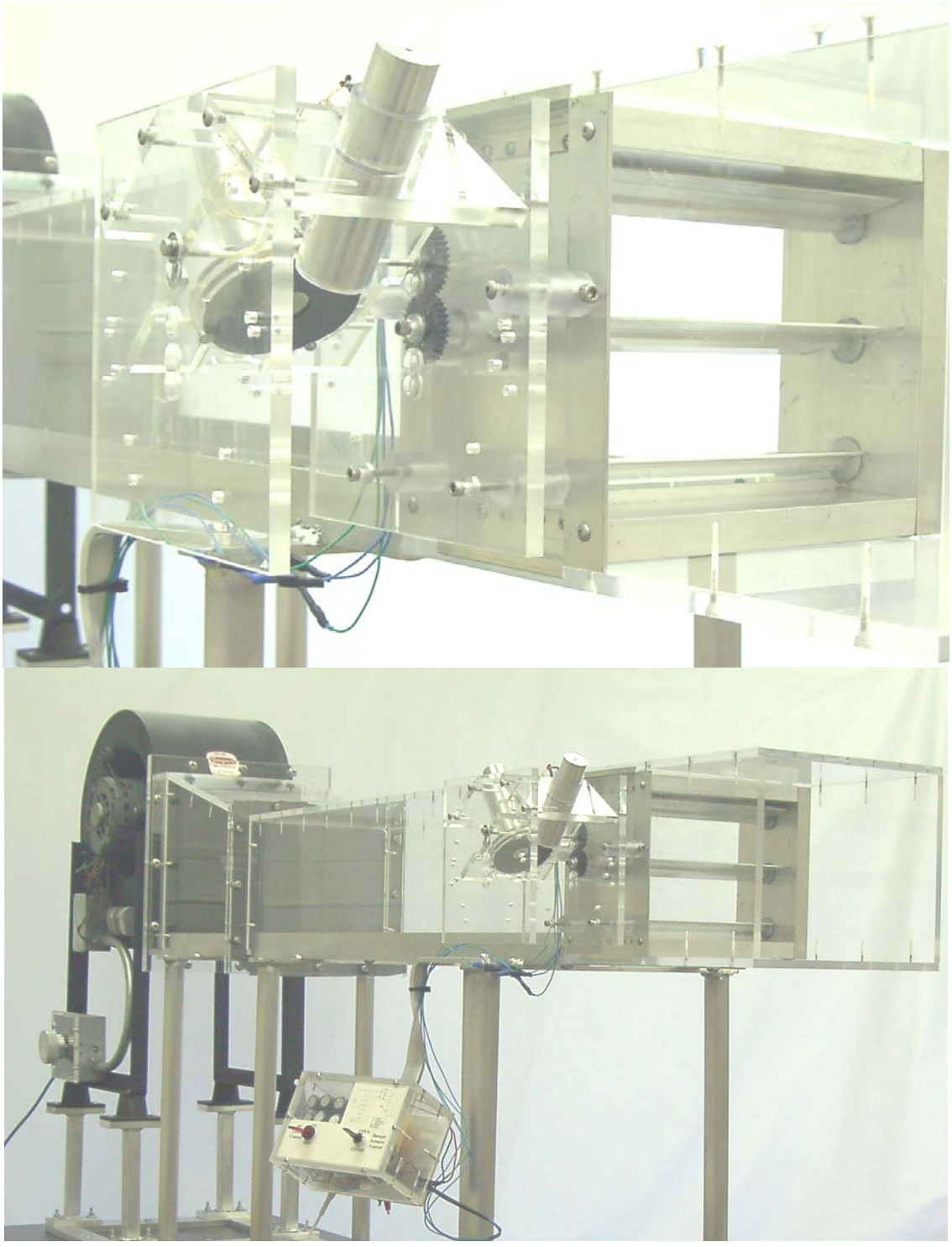


Figure 5: Experimental set-up

The range of angles from open to closed is about 100°. The applied moments required to open and close the louvers were measured (See Fig. 6) using an electronic torque wrench (Snap-on TQJE1000 Electrotork Meter) connected to the fixture shown in Fig. 7. The volumetric flow rate was 1000 cfm.

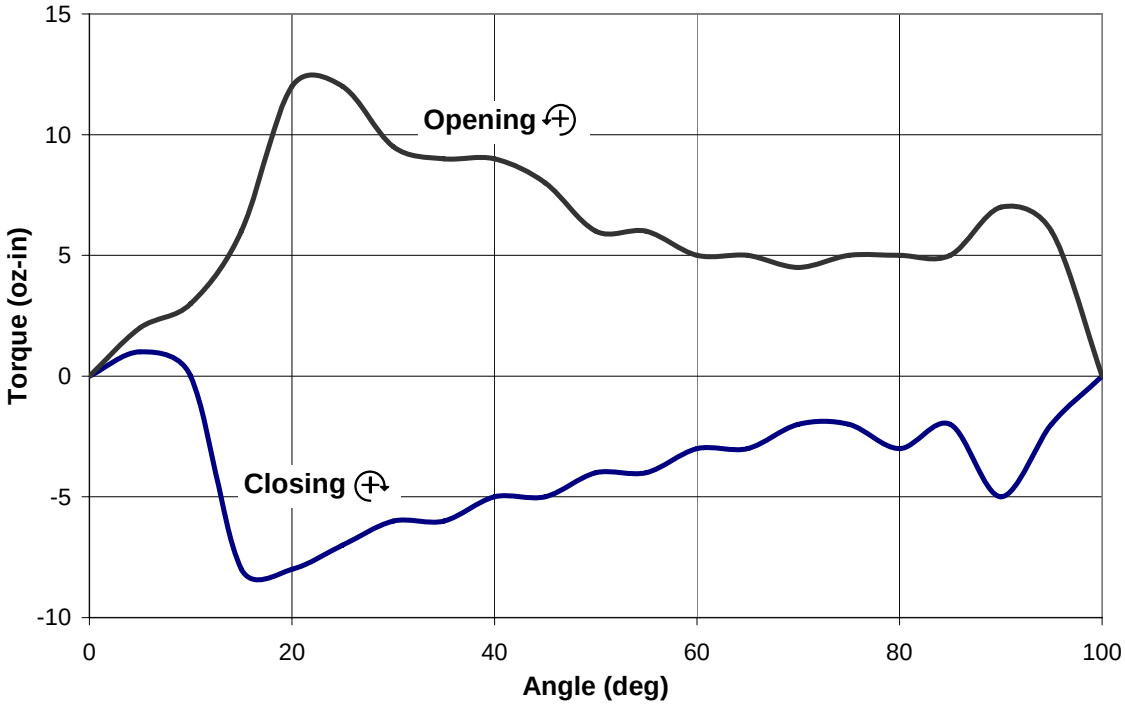


Figure 6: Torques to open and close the louvers

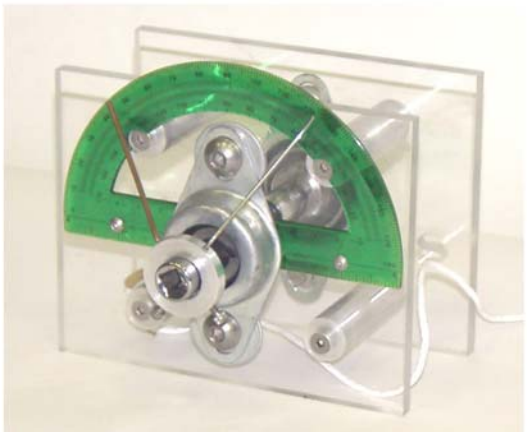


Figure 7: Electronic torque wrench and fixture

The torque was applied clockwise to open and counter-clockwise to close. Notice in Fig. 4 that the force required to open the damper is always positive, and much larger than the torque required to close the damper. The air flow acts to close the damper when the angle of the louver is rotated to approximately 12° measured from fully open.

The electrical work done by the electromagnets is $U_{E1-2} = \int_{(1)}^{(2)} Vidt$. The electrical work produces a transient electromagnetic field that polarizes a permanent magnet and moves a louver and a dynamic element from one state to another. The work done to move the dynamic element and part of the work associated with the electromagnetic field represent an energy loss. As a basic constraint, we require

(1) $$U_{E1-2} \geq U_{M1-2}$$

Equation (1) bounds the design; it depends on the work performed during the discharging of the circuit and the work performed by the permanent magnet independent of the means by which the translational motion of the magnets is converted into rotational work performed on the louvers.

4. Design Parameters

The subsystems in the control system consist of a circuit, a coil, and a configuration. The following describes the sub-systems and their principle design parameters.

4.1 Circuit Parameters

Magnets can be polarized by a variety of methods, e.g., large permanent magnets, semi-continuous DC magnetizer, ½ cycle magnetizer, DC bias/AC–inrush magnetizer, and impulse magnetizer [8]. For on-board magnetization, such as the case here, the impulse magnetizer is a particularly attractive method.

The impulse magnetizer uses large electrolytic capacitors to store energy. This energy is discharged into a coil winding over several milliseconds [8]. The tunable magnet is an Alnico 5; it is polarized when its magnetic field strength reaches H_0 = 640 Oe (1292.929 A-turns/in). Also, notice that the repulsive force and the attractive force between the permanent magnets differ because the repulsive force fields and the attractive force fields (for the same B) are very different. The polarization that changes the repulsive force into an attractive force and vise versa is nonconservative (accompanies an energy loss that can not be recovered), which is evident from an associated hysteretic effect (See Fig. 8).

The current in the pulse is related to the magnetic field strength H by

$$i = \frac{Hl}{N} \tag{2}$$

where N is number of turns and l is magnet length. The circuit that charges and discharges the capacitors is shown in Fig. 9.

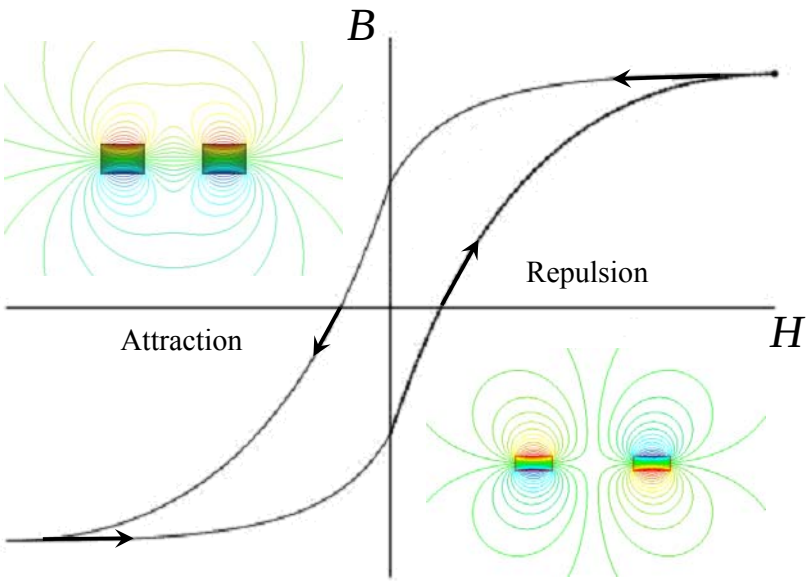


Figure 8: Hysteric fields

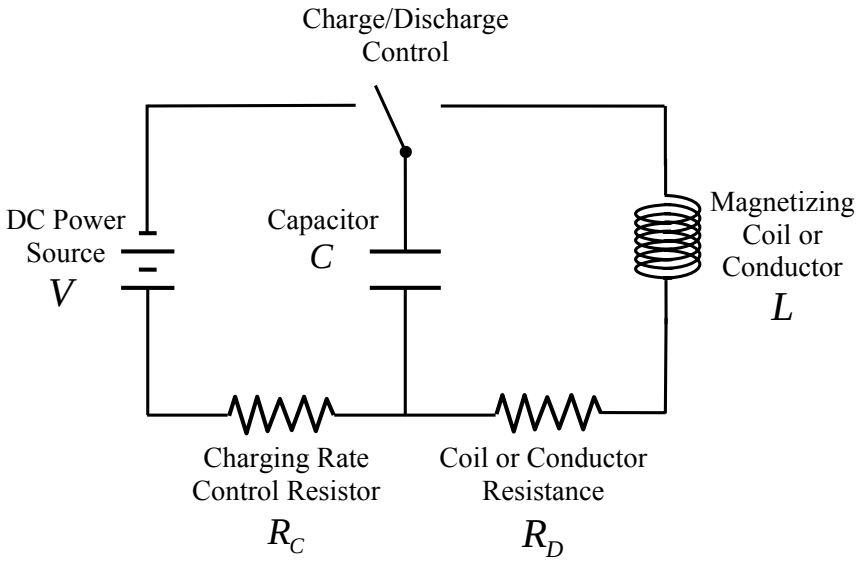


Figure 9: Circuit for impulse magnetizer

The voltage equation of the *RC* circuit (charging) and its solution are (See Figs. 10*a* and 10*b*)

$$V - \frac{q}{C} - R_C \frac{dq}{dt} = 0 \qquad q(t) = VC(1 - e^{\frac{-t}{R_C C}}) \qquad V_C = V(1 - e^{\frac{-t}{R_C C}}) \tag{3}$$

in which $q(0) = 0$ and $\dot{q}(0) = i(0) = \frac{V}{R_C}$. The voltage equation of the *LRC* circuit (discharging) and its solution are (See Figs. 10*c* and 10*d*)

$$L\frac{d^2q}{dt^2} + R_D \frac{dq}{dt} + \frac{1}{C}q = 0 \qquad q(t) = VC\left[e^{r_1 t} + \frac{r_1}{r_2 - r_1}(e^{r_1 t} - e^{r_2 t}) \right]$$
$$i(t) = r_1 VC\left[e^{r_1 t} + \frac{1}{r_2 - r_1}(r_1 e^{r_1 t} - r_2 e^{r_2 t}) \right] \tag{4}$$

in which

$$r_1 = \frac{-R_D}{2L} + \frac{1}{2L}\sqrt{{R_D}^2 - \frac{4L}{C}} \qquad r_2 = \frac{-R_D}{2L} - \frac{1}{2L}\sqrt{{R_D}^2 - \frac{4L}{C}}$$

and $q(0) = Q_{\max} = VC$ and $\dot{q}(0) = i(0) = 0$.

Notice in Figs. 10*a* and 10*b* that the charging time is on the order of 90 seconds and notice in Figs 10*c* and 10*d* that the discharging time is on the order of 1 second.

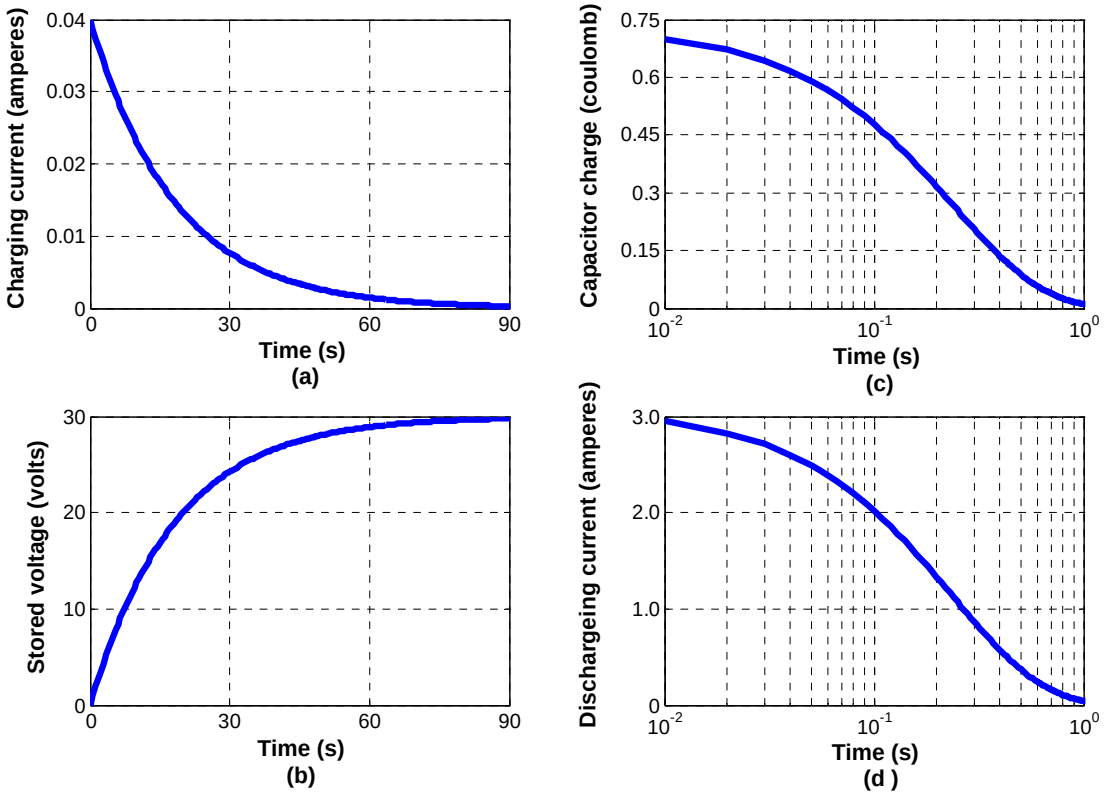


Figure 10: Circuit responses

4.2 Coil Parameters

The current in the coil dictates magnetic field strength while the voltage across the coil is constrained by coil resistance. Coil resistance is proportional to number of turns, from which

$$V_C = \frac{HlR_{TOTAL}}{nN_L} = HlR_W \pi (d_m + d_w N_L) \tag{5}$$

where R_{TOTAL} is total coil resistance, n is number of turns per layer, N_L is the number of layers, R_W is resistance per unit length, d_m is magnet diameter, and d_w is wire diameter. Two wire diameters were considered: 26 gauge for which d_w = 0.018 in and R_W = 0.04 Ω/ft and 18 gauge for which d_w = 0.043 in and R_W = 0.012 Ω/ft. Also, d_m = 0.86 in and Hl = 1040 A-turns. As shown in Fig. 11, the required voltage increases with number of layers and the current decreases with the number of layers. The voltage and outside diameter are shown in Fig. 12. As shown, larger gauge wire allows for lower currents and voltages but packages less tightly.

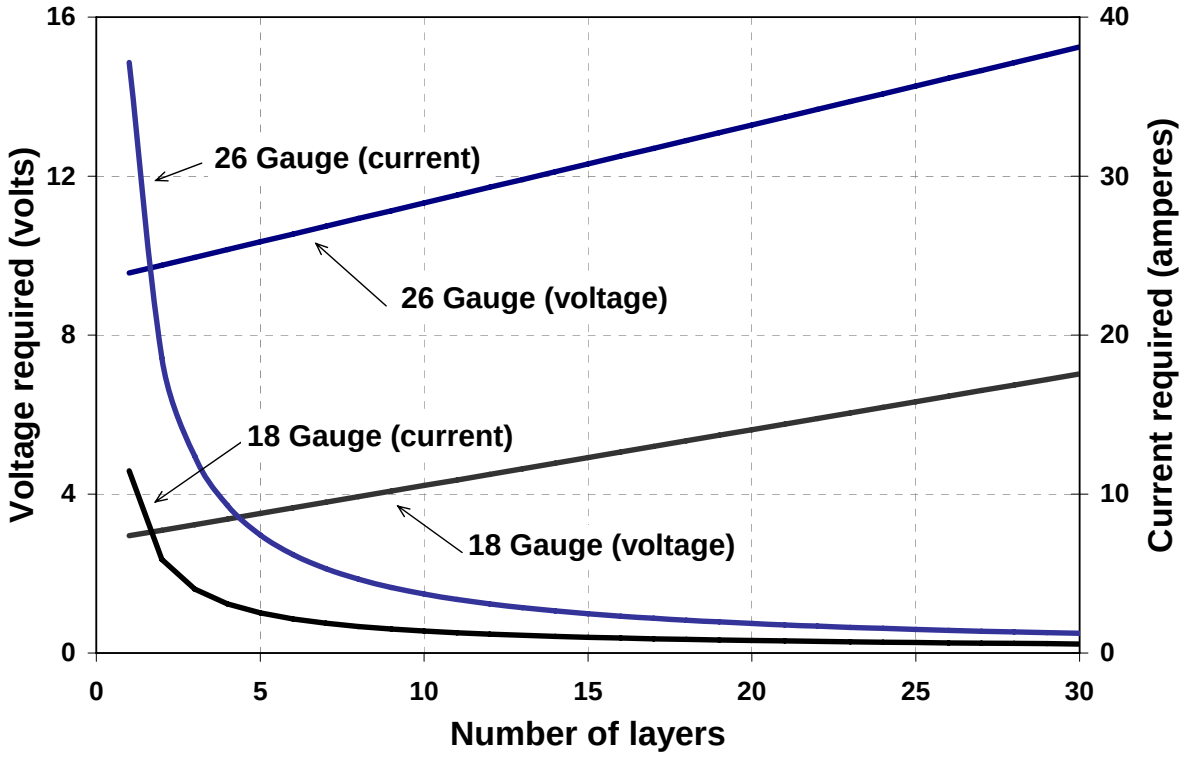


Figure 11: Voltage and current in a wire

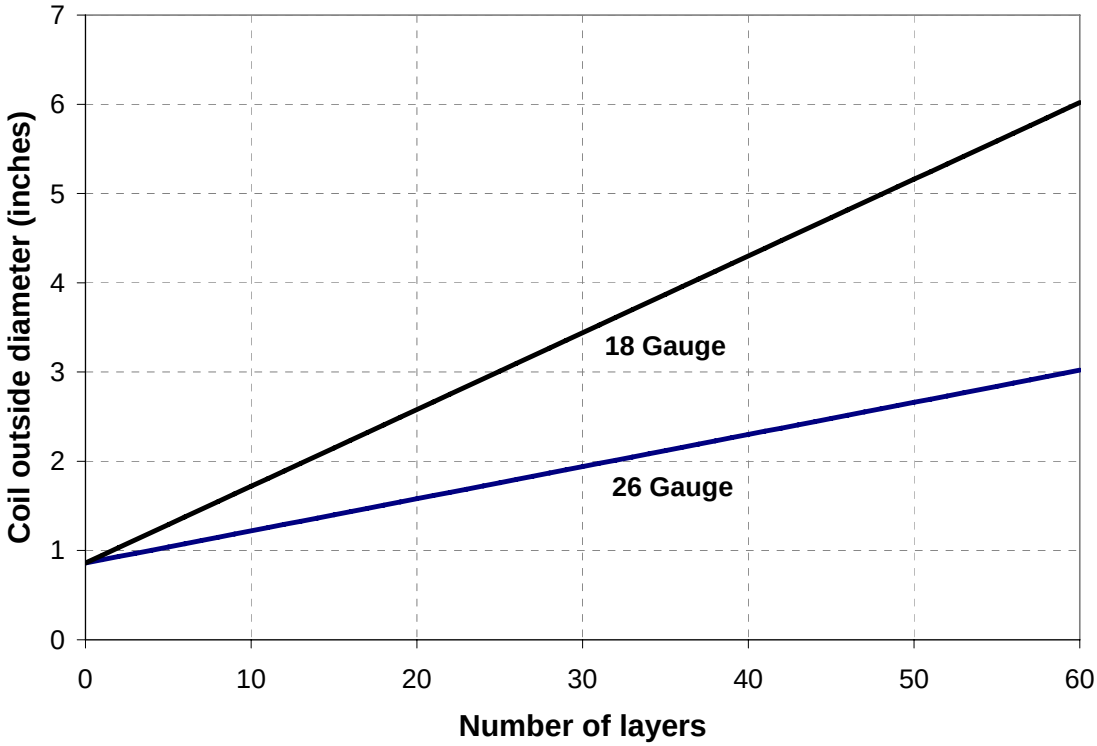


Figure 12: Voltage and outside diameter
(d_m = 0.86 in, l = 0.56 in)

While required voltage increases with number of turns, the current that passes through decreases with number of turns. The maximum current is bound above by the wire's current carrying capacity, i.e., its ampacity. Wire ampacity depends on type of wire and whether it is closely wound or open to air. Furthermore, although standard ampacity ratings do not consider this, it also depends on current duration when the current is a pulse. The ampacity of a wire through which a pulse travels can be several orders of magnitude high than its standard rating.

4.3 Geometric Parameters

The number of magnets and the number of coils in a trans-permanent magnetic system is a matter of design; they can be arranged in a stack [6] or in other configurations [7, 5]. Several different device geometries were evaluated. Two had rotor and stator type designs while one had a pendulum design. The rotor and stator design shown in Fig. 13 and the rotor and stator design shown in Fig. 14 were thought to have instability issues, if the tunable magnets were activated it was believed that the device had the ability to rotate in the wrong direction. The pendulum design, in Fig. 15, is completely stable. When activated it would rotate in the desired direction. Upon further revue of the simple pendulum design, the duties of the magnets were switched, to a configuration of one tunable magnet and two non-tunable magnets as shown in Fig. 16.

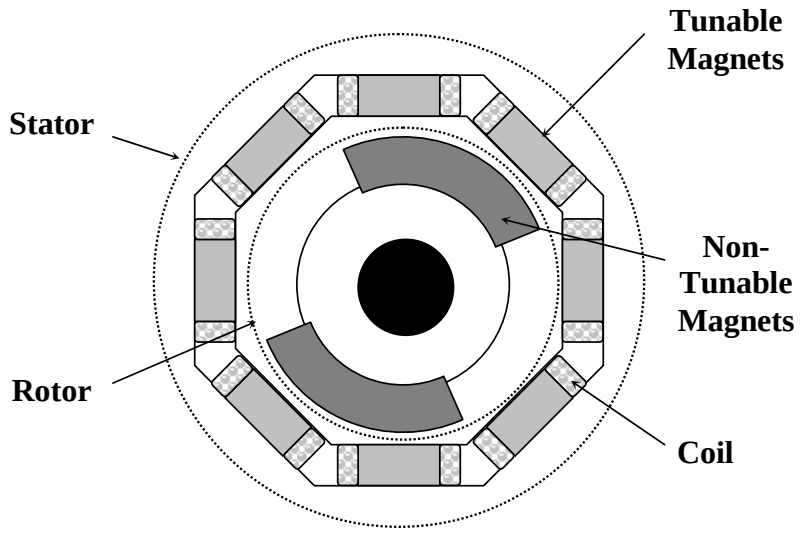


Figure 13: Rotor and stator concept design 1

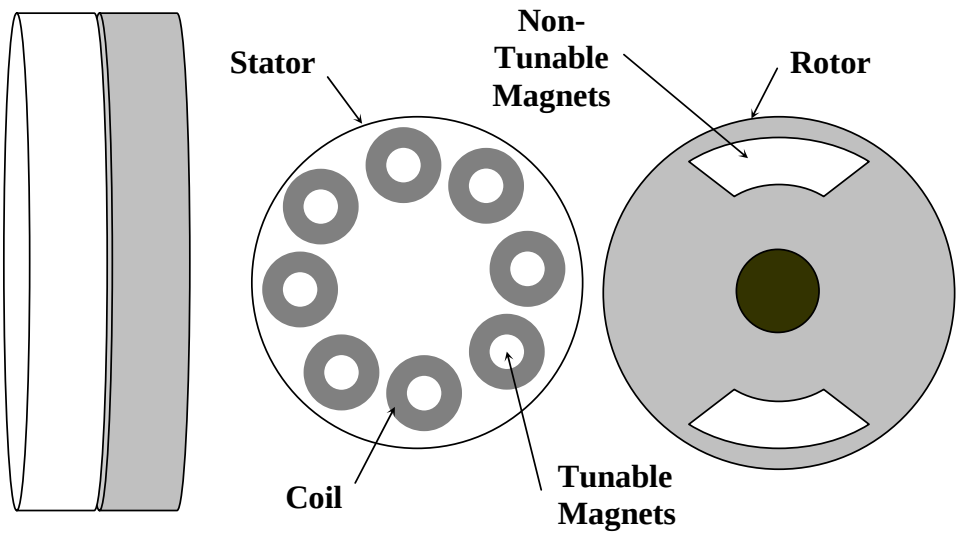


Figure 14: Rotor and stator design concept 2

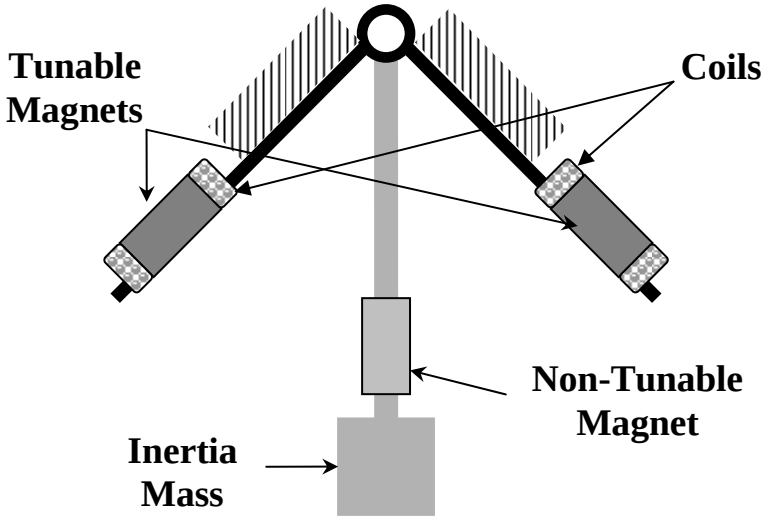


Figure 15: Pendulum design concept

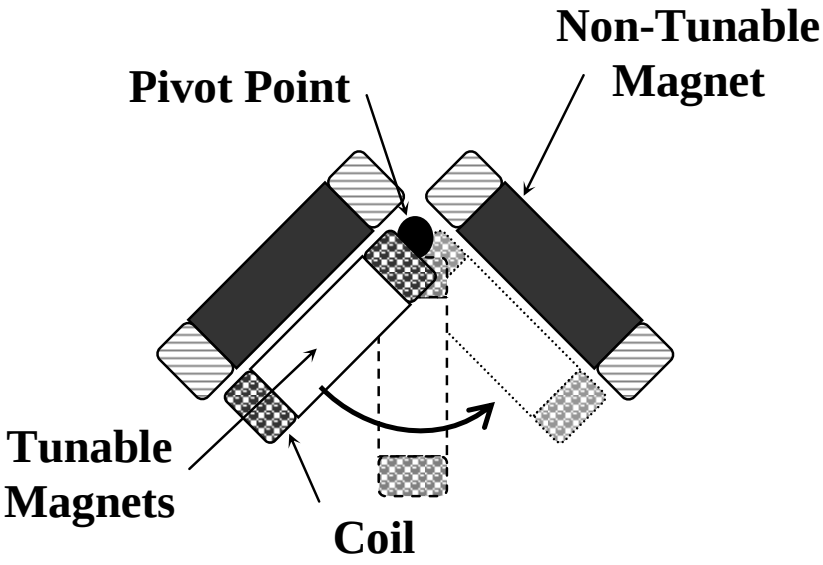


Figure 16: Final design geometry
with 100 degrees of rotation in the tunable magnet

5. Parameter Selection

This section discusses how the trans-permanent magnetics actuator's components were selected and why.

5.1 Circuit Design

First consider the circuit parameters. The first circuit parameter selected was the applied voltage; it was selected to be a low DC voltage provided by a source with a 30V maximum. The charge time of the RC circuit was selected to be rather large – 90 seconds – to prevent rapid switching that could otherwise melt the wire. The charge time was produced using a R_C = 750 Ω charging resistor. The discharge time was set to about 1 second to achieve full pole-switching and to enable the device to benefit from the electromagnetic force during the discharging. The discharge time was produced using C = 0.0282 farads of capacitance. Also a double-pole double-throw switch was used, making it possible to activate the coil in either direction of polarity. The actuator needs to be activated in both directions to flip the magnet's poles back and forth (See Fig. 17).

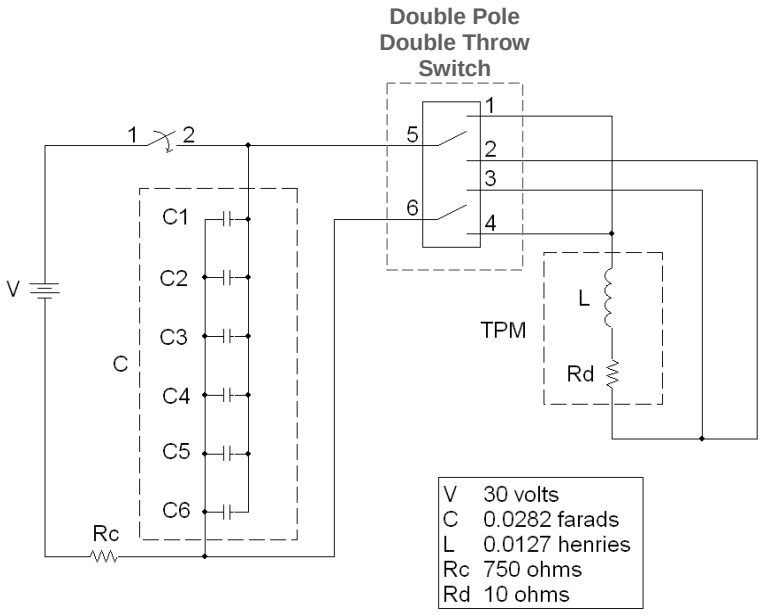
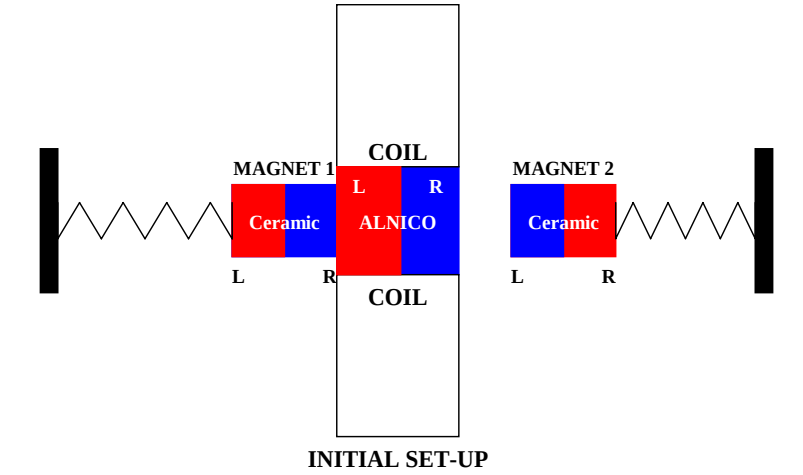


Figure 17: Circuit schematic

5.2 Coil Design

Next, the maximum spool diameter for the coil was selected to be 2.5 in, to allow a maximum of 1260 turns using 26 gauge wire. The 26 gauge wire was selected for its medium size and its standard ampacity rating of about 300 mA. The rapid switching ampacity was estimated to be about 3 A to 4 A (See Fig. 10). The number of turns was selected to be 700. This number produced a coil of manageable size and weight, with a resistance of 10 Ω and an inductance of L = 0.0127 H. The 10 Ω resistance produced a minimum voltage required to flip the poles of the magnet of about 11V. The minimum voltage was calculated using equation (5) in section 4.2. The minimum voltage was also proven using the test apparatus shown in Fig. 18, the test apparatus contains a soft alnico magnet in the center with a coil

around it. Two hard ceramic magnets were place on the sides of the soft magnet and allowed to move in and out to show repulsion and attraction as the polarity of the soft magnet was switched. The test was repeated decreasing the supply voltage until the polarity of the soft magnet ceased to switch. The test results for several configurations are shown in Appendix A, and a video shows samples of the tests (click HERE to see the coil testing video). Figure 18 shows the configuration of the tests.



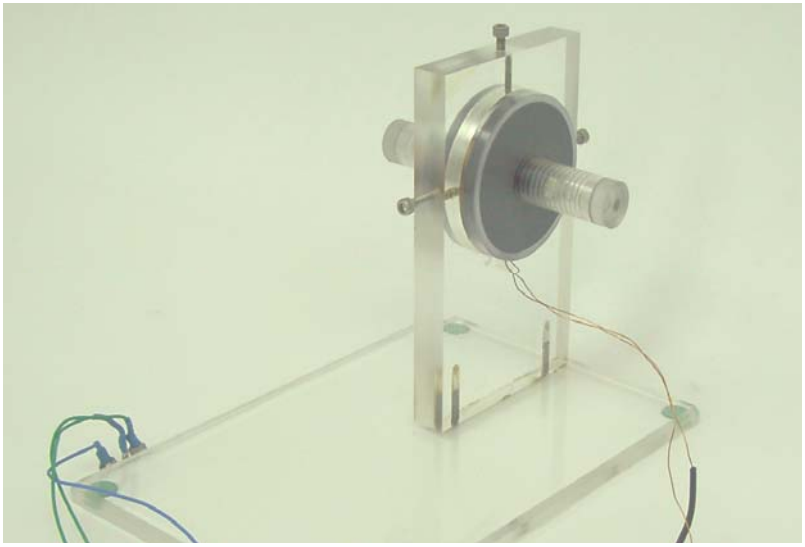
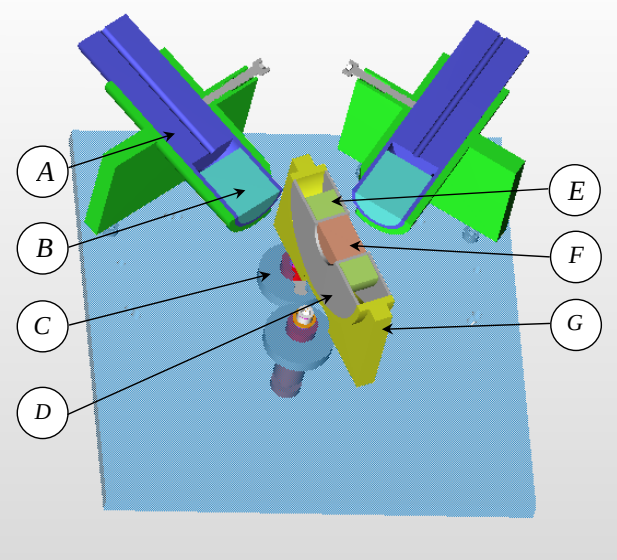


Figure 18: Impulse magnetizer testing apparatus

5.3 Geometry Selection

In this thesis, the magnets were arranged in a hard-soft-hard angular stack, in which the soft magnet is surrounded by a coil and rotates and the two hard magnets are fixed (See Fig. 19). In the final design, a minimal number of magnets were used, only one coil, and an ability to adjust the range of rotation of the soft magnet, through gearing, was included. The tunable permanent magnet was chosen to be an alnico 5 plug magnet with a l = 0.52 in thickness and a d_m = 0.76 in diameter; the non-tunable permanent magnets were selected to be ceramic 5 plug magnets of l = 1.0 inch length and d_m = 0.86 in diameter. With the alnico 5 plug magnet and a coil with 700 turns, the coils inner diameter became d = 0.86 in, its outer diameter became 1.76 in, and the diameter of the spool became d = 2.5 in. The prototype and magnet technical specifications are given in Appendix B.



Symbol	Part
A	Holding material
B	Non-tunable magnet
C	Drive gear
D	Spool
E	Coil
F	Tunable magnet
G	Rotor

Figure 19: Actuator

As shown, the axis of rotation of the soft magnet is geared to the axis of rotation of the louvers. The gearing provides some flexibility in the mechanical conversion between the rotation of the soft magnet and the rotation of the louvers. The gearing can be used to adjust the range of rotation of the soft magnet. Figure 20 shows the principle design parameters.

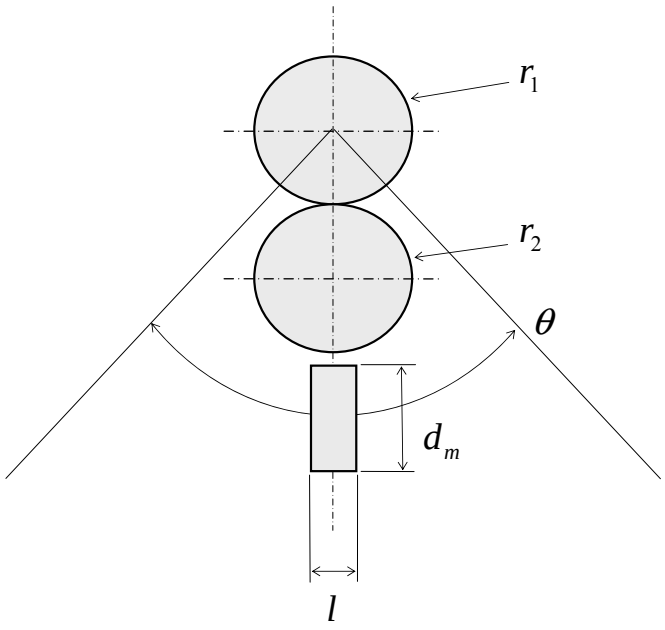


Figure 20: Mechanical conversion between louver rotation and magnet rotation

6. Test Results

The performance of the assembled system was dictated, largely, by the performance of the pre-assembled parts. In its assembled state, the capacitance of the circuit was varied and for each capacitance a breakdown voltage was measured. The breakdown voltage was defined as the minimum voltage for which the pulse would successfully change the state of the louvers from open to closed and from closed to open (See Fig. 21).

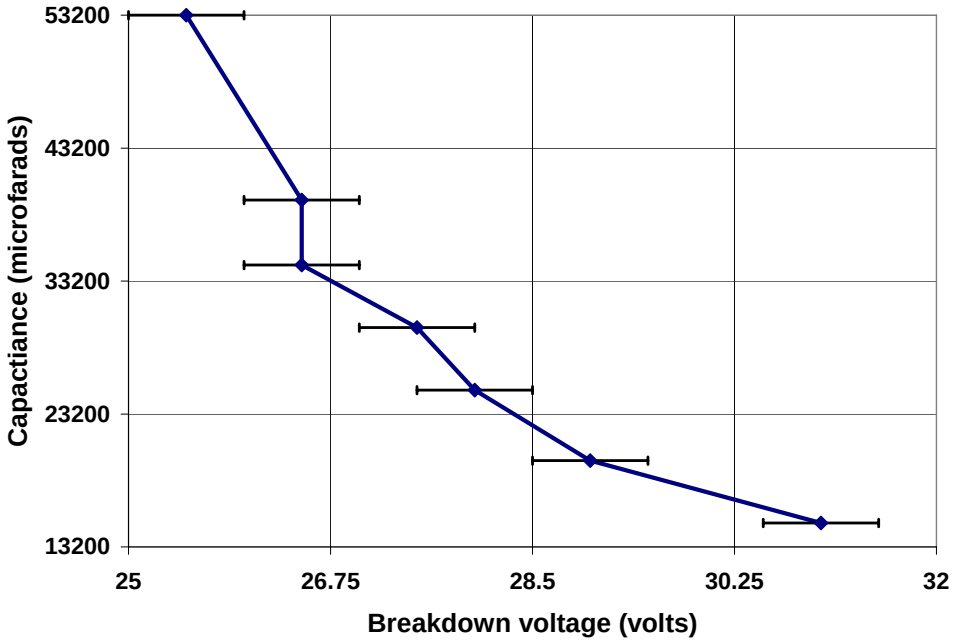


Figure 21: Breakdown voltage

Figure 22 show close-ups of the prototype and test set-up. A video shows the operation of the damper without and with a 1000 cfm flow through the duct (click HERE to see the prototype testing video). The video also shows an example of soft latching.

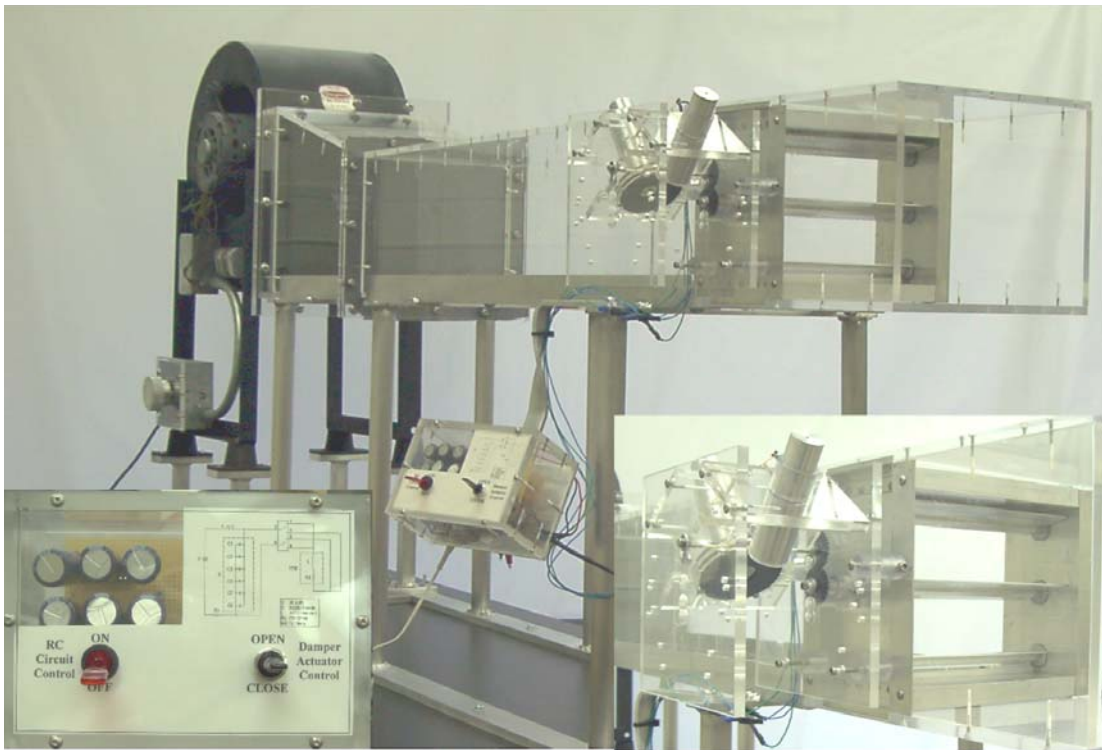


Figure 22: Prototype and test set-up

7. Summary and Conclusions

This thesis studied the feasibility of controlling HVAC dampers by trans-permanent magnetics. A brief literature review was given in section 2, the problem was explained in section 3, the design parameters were identified in section 4, section 5 described how the parameters were selected, and section 6 presented a few test results. In general, the thesis shows that HVAC dampers can be designed by trans-permanent magnetics without coming up against the boundary of the design space – at least in the application considered. The performance was demonstrated in the presence of a moderate level of flow, higher than is typically found in residential and commercial settings. The gearing was left un-optimized at one-to-one. The coils and windings used standard, readily available magnets, and the number of windings was relatively small. In commercial applications, it is conceivable that the size of the actuator could be reduced by an order of magnitude, making it possible to package in a similar or smaller size than is found in controllers of HVAC dampers that are currently available. Some of the other properties observed were

1. Soft latching eliminates the failure mode of mishandling
2. The soft magnets, because they are re-magnetized, do not loose field strength over time.
3. Latching is accomplished without introducing moving parts.
4. The latching function compliments the switching function (the corresponding forces are in the same direction)
5. The circuit and the windings are elementary.
6. The parts and assembly are unsophisticated.

8. References

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Appendix A: Trans-permanent Magnetic Coil Testing

In order to prove the accuracy of the trans-permanent magnetic equation (5) discussed in section 4.2, the following test data was taken for different capacitance levels.

Table 1: Coil testing configuration 1 with 0.0141 farads of capacitance

Rc	Ohms	750
C	Farads	0.0141
L	Henries	0.0329
Rd	Ohms	14.4132
l	Inches	0.52
N	Turns	924

				TPM magnet before activation		Left magnet				Right magnet					
V	Vc	Switch 1 on time	Switch 2 throw direction	R-Pole	L-Pole	L-Pole	R-Pole	Rear mark start	Rear mark end	L-Pole	R-Pole	Rear mark start	Rear mark end	Hc (Coil)	Safety factor
(Volts)	(Volts)	(Sec)	(Fwd/Rev)	(N/S)	(N/S)	(N/S)	(N/S)	# Ticks	# Ticks	(N/S)	(N/S)	# Ticks	# Ticks	Amp turns/inch	
30	29.4	60	Fwd	N	S	S	N	2	5	N	S	5	2	3698.53276	2.433245234
30	29.5	60	Rev	S	N	S	N	5	2	N	S	2	5	3698.53276	2.433245234
29	28.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3575.24833	2.352137059
29	28.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3575.24833	2.352137059
28	27.7	60	Fwd	N	S	S	N	2	5	N	S	5	2	3451.9639	2.271028885
28	27.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3451.9639	2.271028885
27	26.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3328.67948	2.18992071
27	26.6	60	Rev	S	N	S	N	5	2	N	S	2	5	3328.67948	2.18992071
26	25.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3205.39505	2.108812536
26	25.8	60	Rev	S	N	S	N	5	2	N	S	2	5	3205.39505	2.108812536
25	24.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3082.11063	2.027704361
25	24.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3082.11063	2.027704361
24	23.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2958.8262	1.946596187
24	23.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2958.8262	1.946596187
23	22.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2835.54178	1.865488013
23	22.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2835.54178	1.865488013
22	21.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2712.25735	1.784379838
22	21.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2712.25735	1.784379838
21	20.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2588.97293	1.703271664
21	20.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2588.97293	1.703271664
20	19.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2465.6885	1.622163489
20	19.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2465.6885	1.622163489
19	18.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2342.40408	1.541055315
19	18.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2342.40408	1.541055315
18	17.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2219.11965	1.45994714
18	17.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2219.11965	1.45994714
17	16.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2095.83523	1.378838966
17	16.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2095.83523	1.378838966
16	15.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	1972.5508	1.297730791
16	15.9	60	Rev	S	N	S	N	5	2	N	S	2	5	1972.5508	1.297730791
15	15	60	Fwd	N	S	S	N	2	5	N	S	5	2	1849.26638	1.216622617
15	15	60	Rev	S	N	S	N	5	2	N	S	2	5	1849.26638	1.216622617
14	14	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1725.98195	1.135514442
14	14	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1725.98195	1.135514442
13	13	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1602.69753	1.054406268
13	13	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1602.69753	1.054406268
12	12	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1479.4131	0.973298093
12	12	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1479.4131	0.973298093
11	11	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1356.12868	0.892189919
11	11	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1356.12868	0.892189919
10	10	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1232.84425	0.811081745
10	10	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1232.84425	0.811081745

Table 2: Coil testing configuration 2
with 0.0094 farads of capacitance

Rc	Ohms	750
C	Farads	0.0094
L	Henries	0.0329
Rd	Ohms	14.4132
l	Inches	0.52
N	Turns	924

				TPM magnet before activation		Left magnet				Right magnet					
V	Vc	Switch 1 on time	Switch 2 throw direction	R-Pole	L-Pole	L-Pole	R-Pole	Rear mark start	Rear mark end	L-Pole	R-Pole	Rear mark start	Rear mark end	Hc (Coil)	Safety factor
(Volts)	(Volts)	(Sec)	(Fwd/Rev)	(N/S)	(N/S)	(N/S)	(N/S)	# Ticks	# Ticks	(N/S)	(N/S)	# Ticks	# Ticks	Amp turns/inch	
30	29.4	60	Fwd	N	S	S	N	2	5	N	S	5	2	3698.53276	2.433245234
30	29.5	60	Rev	S	N	S	N	5	2	N	S	2	5	3698.53276	2.433245234
29	28.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3575.24833	2.352137059
29	28.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3575.24833	2.352137059
28	27.7	60	Fwd	N	S	S	N	2	5	N	S	5	2	3451.9639	2.271028885
28	27.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3451.9639	2.271028885
27	26.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3328.67948	2.18992071
27	26.6	60	Rev	S	N	S	N	5	2	N	S	2	5	3328.67948	2.18992071
26	25.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3205.39505	2.108812536
26	25.8	60	Rev	S	N	S	N	5	2	N	S	2	5	3205.39505	2.108812536
25	24.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3082.11063	2.027704361
25	24.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3082.11063	2.027704361
24	23.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2958.8262	1.946596187
24	23.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2958.8262	1.946596187
23	22.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2835.54178	1.865488013
23	22.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2835.54178	1.865488013
22	21.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2712.25735	1.784379838
22	21.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2712.25735	1.784379838
21	20.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2588.97293	1.703271664
21	20.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2588.97293	1.703271664
20	19.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2465.6885	1.622163489
20	19.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2465.6885	1.622163489
19	18.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2342.40408	1.541055315
19	18.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2342.40408	1.541055315
18	17.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2219.11965	1.45994714
18	17.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2219.11965	1.45994714
17	16.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2095.83523	1.378838966
17	16.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2095.83523	1.378838966
16	15.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	1972.5508	1.297730791
16	15.9	60	Rev	S	N	S	N	5	2	N	S	2	5	1972.5508	1.297730791
15	15	60	Fwd	N	S	S	N	2	5	N	S	5	2	1849.26638	1.216622617
15	15	60	Rev	S	N	S	N	5	2	N	S	2	5	1849.26638	1.216622617
14	14	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1725.98195	1.135514442
14	14	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1725.98195	1.135514442
13	13	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1602.69753	1.054406268
13	13	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1602.69753	1.054406268
12	12	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1479.4131	0.973298093
12	12	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1479.4131	0.973298093
11	11	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1356.12868	0.892189919
11	11	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1356.12868	0.892189919
10	10	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1232.84425	0.811081745
10	10	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1232.84425	0.811081745

Table 3: Coil testing configuration 3
with 0.0047 farads of capacitance

Rc	Ohms	750
C	Farads	0.0047
L	Henries	0.0329
Rd	Ohms	14.4132
l	Inches	0.52
N	Turns	924

				TPM magnet before activation		Left magnet				Right magnet					
V	Vc	Switch 1 on time	Switch 2 throw direction	R-Pole	L-Pole	L-Pole	R-Pole	Rear mark start	Rear mark end	L-Pole	R-Pole	Rear mark start	Rear mark end	Hc (Coil)	Safety factor
(Volts)	(Volts)	(Sec)	(Fwd/Rev)	(N/S)	(N/S)	(N/S)	(N/S)	# Ticks	# Ticks	(N/S)	(N/S)	# Ticks	# Ticks	Amp turns/inch	
30	29.4	60	Fwd	N	S	S	N	2	5	N	S	5	2	3698.532755	2.433245234
30	29.5	60	Rev	S	N	S	N	5	2	N	S	2	5	3698.532755	2.433245234
29	28.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3575.24833	2.352137059
29	28.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3575.24833	2.352137059
28	27.7	60	Fwd	N	S	S	N	2	5	N	S	5	2	3451.963905	2.271028885
28	27.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3451.963905	2.271028885
27	26.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3328.67948	2.18992071
27	26.6	60	Rev	S	N	S	N	5	2	N	S	2	5	3328.67948	2.18992071
26	25.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	3205.395055	2.108812536
26	25.8	60	Rev	S	N	S	N	5	2	N	S	2	5	3205.395055	2.108812536
25	24.6	60	Fwd	N	S	S	N	2	5	N	S	5	2	3082.110629	2.027704361
25	24.7	60	Rev	S	N	S	N	5	2	N	S	2	5	3082.110629	2.027704361
24	23.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2958.826204	1.946596187
24	23.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2958.826204	1.946596187
23	22.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2835.541779	1.865488013
23	22.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2835.541779	1.865488013
22	21.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2712.257354	1.784379838
22	21.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2712.257354	1.784379838
21	20.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2588.972929	1.703271664
21	20.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2588.972929	1.703271664
20	19.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2465.688503	1.622163489
20	19.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2465.688503	1.622163489
19	18.8	60	Fwd	N	S	S	N	2	5	N	S	5	2	2342.404078	1.541055315
19	18.8	60	Rev	S	N	S	N	5	2	N	S	2	5	2342.404078	1.541055315
18	17.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2219.119653	1.45994714
18	17.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2219.119653	1.45994714
17	16.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	2095.835228	1.378838966
17	16.9	60	Rev	S	N	S	N	5	2	N	S	2	5	2095.835228	1.378838966
16	15.9	60	Fwd	N	S	S	N	2	5	N	S	5	2	1972.550803	1.297730791
16	15.9	60	Rev	S	N	S	N	5	2	N	S	2	5	1972.550803	1.297730791
15	15	60	Fwd	N	S	S	N	2	5	N	S	5	2	1849.266378	1.216622617
15	15	60	Rev	S	N	S	N	5	2	N	S	2	5	1849.266378	1.216622617
14	14	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1725.981952	1.135514442
14	14	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1725.981952	1.135514442
13	13	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1602.697527	1.054406268
13	13	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1602.697527	1.054406268
12	12	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1479.413102	0.973298093
12	12	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1479.413102	0.973298093
11	11	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1356.128677	0.892189919
11	11	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1356.128677	0.892189919
10	10	60	Fwd	N/A	N/A	S	N	2	2	N	S	2	2	1232.844252	0.811081745
10	10	60	Rev	N/A	N/A	S	N	2	2	N	S	2	2	1232.844252	0.811081745

Appendix B: Material Technical Specifications

Table 4: Magnetic material properties

	Ceramic 5	Alnico 5
Residual Magnetization B_r	3800 *Gauss*	12800 *Gauss*
Coercivity Force H_c	2400 *Oersteds*	640 *Oersteds*
Intrinsic Coercivity Force H_{ci}	2420 *Oersteds*	640 *Oersteds*
Energy Product $BH_{\max}$	3.4 *MGO*	5.5 *MGO*

Table 5: T-PM component measurements

Spool	Outside diameter, *in* Inside thickness, *in* Outside thickness, *in*	2.5 0.522 0.622
Magnets	<u>Alnico 5:</u> Diameter: *in* Length: *in* <u>Ceramic 5:</u> Diameter, *in* Length, *in*	 0.758 0.522 0.862 0.999
Coil	Number of turns Type of wire Inductance, *henries* Resistance, *ohms*	700 26 AWG 0.0127 10.0